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APPLICATION OF THE POLAR-FRONT THEORY TO A SERIES OF AMERICAN WEATHER MAPS[1]

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SYNOPSIS

1. In order to show the applicability of the polar-front theory to the study of American weather a series of synoptic maps, comprising the period February 16–19, 1926, has been subjected to a detailed analysis by the methods of the Norwegian Meteorological School. The type discussed below, a weak depression from the Northwest slowly approaching the lower Mississippi Valley, and there increasing in intensity under advection of warm, moist air from the Gulf and cold air from Canada, occurs frequently. It offers a good example for analysis, as the depression is built up of at least four different air masses. It is found that in spite of the few data from the West the history of the LOW can be satisfactorily outlined, at least in its general features.

2. The methods used in locating the fronts are discussed, several examples being given.

3. The upper-air data are discussed and employed for identification of the different air masses. The free-air temperatures prove very valuable for this purpose, since in the upper levels the air masses seem to a great extent to preserve their characteristic temperatures.

4. The aerological data are also used for a discussion of the stability of the atmosphere over the Gulf States. In this connection upper-air convection in the South is treated and reasons given why this kind of convection plays such an important rôle in the United States while it is almost without significance in Europe.

5. As a result of the analysis of the maps according to the polar-front theory it is found that several improvements in the character and amount of the observations in this country are highly desirable and some suggestions to that effect are offered.

INTRODUCTION

In this article are given the results of a study of weather maps carried on by the authors in the summer and fall of 1926. In taking up this work, the intention was to show in the first place how and to what extent the Norwegian methods of analyzing synoptic maps could be applied to the study of American weather. Furthermore, it seemed desirable to ascertain what modifications, if any, in these theories would be required and finally to determine whether any change in the present system of observations might be needed in order to facilitate an application of the Norwegian methods to the daily forecast work in the United States. With these objects in mind it was decided to follow in detail the movements of the different air masses and fronts on a selected series of weather maps. It would, of course, have been possible to take a synoptic chart showing a cyclone of clear-cut structure with a well marked warm sector but the application of the polar-front theory to such a special case would not have given a satisfactory answer to the general question of whether or not a satisfactory determination of fronts is possible on our maps in general and also whether it is possible to understand the physical processes in operation. A series was therefore selected which, so far as complexity is concerned, leaves nothing to be desired. The maps chosen afford examples of occlusions, a regeneration and a formation of a secondary according to the wave theory of cyclones. We are well aware that in certain details several of the conclusions reached may be subject to error but, it is believed that in the main our analysis describes the behavior of the fronts correctly.

The first section contains a general description of the synoptic charts with special reference to the fronts and precipitation areas. To follow this part to the best advantage, frequent reference to the lithograph maps 1 to 7 is necessary. In the next section are given a few examples of the methods pursued in locating the fronts The third section is devoted to a study of available free air data for the period under discussion. So far as possible, they have been used to verify the location and movements of the fronts. Section four treats the question of upper air convection which, in the papers published heretofore by the Norwegian school, has been almost entirely left out of consideration but which is essential for the explanation of certain types of cyclonic rain in the United States. Finally in the last section suggestions are offered as to desirable extensions in the network of stations and additional data to be included in the telegraphic reports of observations. The reader is supposed to be familiar with the fundamentals of the modern ideas concerning the structure of cyclones (*see* bibliography).

I. DESCRIPTION OF THE FRONTS AND PRECIPITATION AREAS

The period under discussion extends from February 16, 8 a. m. to February 19, 8 a. m., 1926. Maps for 8 a. m. and 8 p. m. each day are reproduced and numbered 1 to 7, an explanation of the symbols and notations being given on each map.[2]

For several days prior to the 16th, as shown by the northern hemisphere weather charts, a low pressure area moved slowly eastward over the Aleutian Islands, while south of its center several secondaries moved eastward to the North Pacific Coast. One of these, attended by a warm front, reached the North Pacific Coast on the 14th, at which time a cold front was some distance off the California coast. On the evening of the 15th the rain belt along this warm front covered southern Washington and the greater part of Idaho, while the air behind the cold front, C_p, had overspread Northern California as indicated by the double red line marked "February 15, p. m." on map 1. By the morning of the 16th it had overtaken the warm front and an occlusion took place with rain over southern Washington and northwestern Idaho.

As frequently occurs in such cases, the low center was apparently displaced to the south or southeast of the occlusion, the low center D_1 on the morning of the 16th being central over Utah. The warm front, W_1, may be

[1] This study was begun during a temporary appointment of Mr. Rossby in the Weather Bureau but was completed during his employment under "The Daniel Guggenheim Fund for the Promotion of Aeronautics."

[2] Temperatures given in this paper are in Fahrenheit unless otherwise indicated.

continued southward through Utah and Arizona, and thence southeastward through the Rio Grande Valley. It may be connected with a cold front C_1 over the southern Gulf and western Atlantic. This cold front C_1, attended the eastward movement of a trough of low pressure off the Atlantic Coast, and has by the morning of the 16th advanced eastward nearly to Bermuda and southward to the Florida Straits. Behind C_1 a deep mass of cold air P_1 has accumulated over the Atlantic States and Ohio Valley (see Sec. III, also Fig. 4). As a result the pressure system shows an anticyclone, H_1, central over the Ohio Valley, the origin of which may be traced to Alberta. During its movement southeastward it has left behind a thin layer of polar air over the Plains States, the West Gulf States and upper Mississippi Valley. Above this thin layer we find (see Sec. III) a relatively mild dry westerly wind which will be designated the M current, but which will serve as polar air relative to the depression D_1. Between the warm front W_1 and the cold front C_p we have a warm sector made up of a current of comparatively warm air of Pacific origin, T_p.

The anticyclone H_2 is increasing in intensity over a snow covered region and more and more cold air, P_2, is accumulating behind the cold front, C_2. When sufficient polar air has accumulated this cold mass will tend to move southward in the form of a more or less well-developed cold wave, which in the developments to follow will be of great importance.

On map 2 (Feb. 16, p. m.) the depression, D_1, has moved southeastward, being central over Colorado. From this center the occluded front, which is gradually disappearing, extends northwestward. The fresh polar air, P_2, from the Canadian Northwest is spreading southward and the western part of the cold front, C_2, now almost coincides with the occlusion. The polar air, P_2, is much colder than the Pacific air, P_p, behind the occlusion and we may therefore expect that the former will partly push away the Pacific air and spread southward on the western side of D_1.

In the South, warm, moist air, T_m, from the Gulf has begun to move northward over the thin layer of polar air (P_1) covering the West Gulf States, and this ascent over a heavier air mass has given rise to the development of a rain area over southern Texas.

The depression, D_2, is now located northwest of Lake Superior and the circulation has increased somewhat in intensity. A regular warm front rain belt has developed northeast and east of Lake Superior, but the mild M air is still separated from the ground by a thin layer of P_1 air, so that no real warm air is discernible at the surface. This mild M air over Wisconsin and Iowa seems to be flowing in a valley between the colder P_2 air over the Dakotas and the cold P_1 air remaining over the Atlantic States and the Ohio Valley.

On map 3 (Feb. 17, a. m.) the depression, D_1, has been displaced still farther southward under the influence of

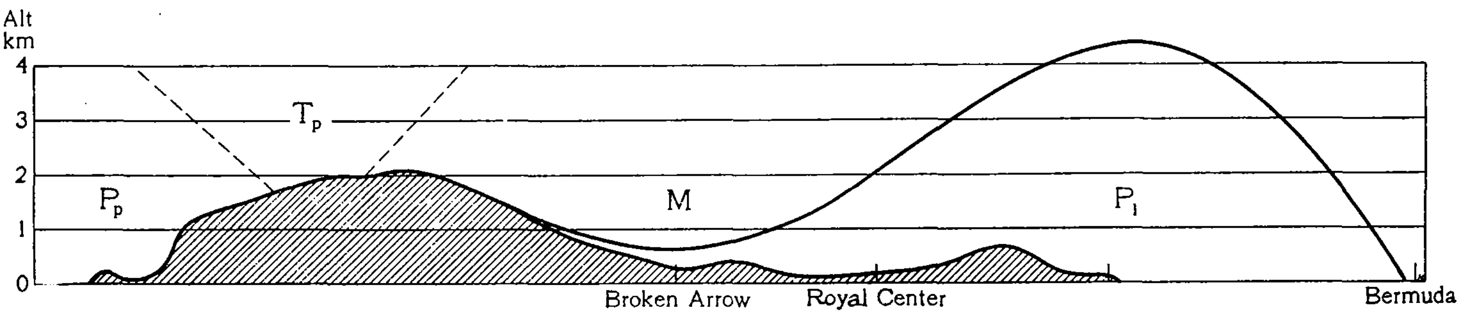


FIG. 1.—Vertical section of the atmosphere along latitude 37°, February 16, 8 a. m.

The LOW D_2 over Manitoba has advanced southeastward from British Columbia. This LOW is maintained by the relatively warm M air and the cold P_2 current over Saskatchewan, but, since the M air is separated from the ground by the thin layer of P_1 air mentioned before, the depression has no well-developed warm sector at the surface.

The origin of the upper current over the Plains States and upper Mississippi Valley is somewhat uncertain, but, judging from its low humidity, it can not be of Gulf origin, but must have come at least in major part across the mountains from the Pacific. Kite ascents at Drexel and Ellendale show that this mild air appears as low down as 500 m.

To illustrate the distribution of the different air masses, a vertical section for the 16th 8 a. m. is given along latitude 37°. (See Fig. 1.) With the aid of the upper air data from Washington, Broken Arrow and Royal Center (afternoon flight) it has been possible to draw fairly well the boundary between the M and the P_1 air. It is not possible to determine the boundaries between the P_p, T_p, and M currents on account of the absence of upper air data from the Western States, but considering the relative densities of the three air masses as inferred from the surface temperatures and the position of the fronts at the surface, we may conclude that they are distributed approximately as indicated by the broken lines in the figure.

the heavy polar air, P_2, north of it. The occlusion and the western part of the new cold front C_2 have joined and play the rôle of a well-marked secondary cold front to D_1, (C_2). The cold front, C_p, extends from the depression, D_1, southward and then westward over northwestern Mexico. The small rain belts over northern Missouri, lower Michigan, and at Doucet, Quebec, may be explained as a kind of warm front rain. As the P_2 current spreads slowly southeastward the mild M current in front of it, which is made up of several strata the densities of which increase from northwest to southeast, tries to escape to the east. As a result the warmer layers of the M current will slide up along and over the colder ones, in this manner producing a light, warm front rain (St. Joseph 0.06 inch, Grand Haven 0.07, and Doucet 0.10). That the density of the M current actually increases from northwest to southeast, at least in the lower levels, is seen from the morning kite ascents, the temperature at 1,000m being 3.3° C. at Royal Center and 0.7° C. at Washington, and at 1,500 meters 0.7° C. at Royal Center and −0.3° C. at Washington. At higher levels the density changes in the opposite way.

The polar air, P_1, which has been carried around the anticyclone centered over Virginia, has been heated from below through contact with the warm water of the Gulf. This heated polar air will be studied more closely in Section III, and is there denoted as M_1 air. On account of this heating it is very difficult to trace the exact position of the front W_1, which, under the influence of the increasing southerly current, T_m, has begun to move northward. It seems, however, as if northeastern Texas was still covered with a thin layer of heated P_1 air (M_1). The rain belt, which on the preceding map was located over Texas on the northern side of W_1, has moved northeastward during the night and is now over Louisiana and Arkansas. Even in its eastern part the warm front (W_1) has moved slowly northward under the influence of the southwesterly T_m current and seems to be located between Miami and Ft. Myers.

On map 4 we find the depression, D_1, displaced still more to the east and south, being now central over Oklahoma. The cold front, C_p, extends from the center southward to northeastern Mexico and thence probably westward. The western part of the cold front, C_2, extends from D_1 northwestward. In comparing this map with the preceding one, it is seen that the polar air, P_2, is spreading southward to the west of the depression.

The T_m air has now worked down to the surface over the greater part of Texas and southern Louisiana. The warm front, W_1, passes immediately north of New Orleans and continues eastward between Titusville and Jacksonville. The rising pressure north of the front, C_2, shows that the P_2 air mass is slowly pressing the entire system southeastward, lifting the M air and thus producing a broad rain belt along the front.

During the next 12 hours the cold front C_p overtakes the western part of the warm front W_1. As a consequence the rain belt along the latter has almost entirely disappeared on Map 5 (Feb. 18, 8 a. m.), while the rain belt along the eastern part of C_2 remains unchanged in extent. On map 4 the development of a wave-like disturbance off the South Atlantic coast along the eastern part of W_1 was indicated. This wave has continued to develop and move northward simultaneously with the formation of a rain belt over Georgia, the Carolinas and extreme northwestern Florida. This wave, as seen on the following maps, will develop into a secondary with closed isobars.

The western part of the cold front, C_2, has moved entirely around the center of the depression D_1, and the polar air P_2 has reached northern Texas. Thus the Pacific air, P_p is restricted to a rather narrow, spiral form of wedge extending from the Texas coast into the center of D_1.

On map 6 (Feb. 18 p. m.) we find that D_1 has moved eastward. It is now central over southeastern Missouri. The secondary which on the preceding map was central over Georgia has moved northward up the South Atlantic coast and increased in intensity, so that now a separate low pressure center, D_3, is found over North Carolina.

The area of rain over Georgia and northern Florida must be explained to a great extent as due to upper air convection, produced as the warm T_m current penetrates under the somewhat colder T_p current. (See Sec. IV, p. 492.) The convectional character of the rain is obvious from the fact that thunderstorms occurred at Atlanta and Thomasville.

The cold air, P_2, continuing to move southward behind D_1 now covers Texas, and is beginning to spread over the Gulf of Mexico. The cold front C_p has also moved eastward and now extends from Alabama southward. The occluded part of the front continues to decrease in intensity. At the point south of the occlusion where C_p and W_1 branch out there would ordinarily develop a new secondary center D_4. However, the three centers D_1, D_3, and D_4 are so close to each other that the individual circulations around them markedly influence each other and have a tendency to join in a single circulation in the same way that vortex experiments have shown small water whirls rotating in the same direction to have a tendency to join and form a single large whirl.

Map 7 (Feb. 19, 8 a. m.) shows a continued displacement of the center D_1, toward the east. The cold front C_2 has now taken the form of a line extending from New England southwestward to extreme northwestern Florida, behind which the cold air P_2 flows unhindered over the Gulf of Mexico. The D_3 center has moved northward to northern Virginia, while what remains of the D_4 center is over northeastern South Carolina. The front W_1–C_p is still accompanied by an extensive rain belt along the middle and south Atlantic coast, which is clearly separated from the rain belt behind C_2 by a region without precipitation over the southern Appalachians. The whole low pressure system over the Atlantic States has deepened (in other words, the circulation has increased in intensity) during the last 12 hours. The lowest pressure is 29.56 on the 18 p. m. while on the 19 a. m. it is 29.36.

This increase in intensity of the circulation may be explained as a result of the gradual disappearance of the two sectors M and P_p, separating the warm T_m and the cold P_2 currents. Thus the temperature differences at the W_1–C_p and the C_2 fronts are added. In the subsequent developments we may expect the transition layers between T_m and P_2 to disappear entirely and a single well marked discontinuity to develop.

II. EXAMPLES OF METHODS USED IN LOCATING FRONTS

A few examples will be given illustrating how the position of a front is determined by means of the ordinary surface observations.

For this purpose we may start with the warm front W_1 on map 4: We see on this map a rain area extending from the center D_1 over Oklahoma, east southeastward to Alabama. This rain area is of the broad type which generally accompanies a warm front. We should therefore most naturally expect to find some discontinuity in the meteorological elements in that region. In the rain belt the winds are mostly east or southeast, while south of it they are all southerly. Thus, it is logical to place a warm front tentatively along the southern limit of the rain belt. That would mean that we have to explain the rain belt as the result of the up-grade movement of the southerly current over the east and southeasterly winds in the rain belt. If we look a little closer at the data, we find that the temperatures are in good agreement with this hypothesis. Within the southerly current the temperatures vary from 70° at Brownsville and New Orleans to 62° at Fort Worth. In the relatively cold P_1 current, temperatures range from 60° at Shreveport and Mobile to 48° at Little Rock. Thus we see that, while the tentative front is not accompanied by a marked temperature discontinuity, it distinctly separates two air masses which, considered as a whole, are of very different temperatures. Furthermore, the cloud observations confirm the hypothesis that warm air is sliding upward over the colder southeasterly current. Thus Vicksburg with a surface wind from the southeast reports nimbus moving from the southwest and Fort Smith with easterly surface wind reports strato-cumulus from the southwest. Also the cloud observations at Oklahoma and Springfield, Mo., confirm the hypothesis of an upper drift from the south or southwest. The absence of a marked temperature contrast along the front W_1 is what is generally to be expected in the case of warm fronts and is explained by the combination of several factors. The warm front is generally preceded by winds with increasing southerly components which bring in warmer and warmer air masses. Furthermore, due to surface friction the cold air, as it is pushed away by the warm current, will often leave a thin surface layer behind. This layer will gradually mix with the warmer air above and thus prevent a sudden change in temperature or wind direction at the surface.

There is another element which generally is of great value in determining the position of the fronts, namely, the barometric tendency (the pressure change in the two hours preceding the observation). In the case of the passage of a warm front, preceding which warm air gradually works down to the surface from above, the total weight of the air column over a station decreases, thus causing falling pressure ahead of the front and as a corollary, negative tendencies. In the example such negative tendencies are noted at Pensacola and Springfield, Mo. Little Rock shows a pressure rise of .04 inch in apparent disagreement with the above statement, but this inconsistency is explained by the occurrence of a thunderstorm. After the passage of the warm front, when all the cold air has disappeared, the rate of the pressure fall generally decreases, thus giving an inflection in the pressure curve. As the cold front approaches, the southerly current frequently increases, bringing in warmer air, whereby the pressure is further decreased. This continuous pressure fall will tend to diminish the characteristic angle (A) accompanying the passage of the warm front (see fig. 2), but it will accentuate the angle (B) caused by the passage of the cold front.

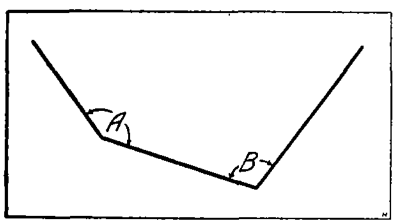


FIG. 2.—Idealized barograph trace during passage of warm sector

As an application of the above idea let us look at the barograph trace at New Orleans (fig. 3). On the morning of the 17th New Orleans was in the cold air with northeast wind, force 3 and a temperature of 58°, while at 8 p. m. the temperature had risen to 70° and the wind changed to south, indicating the passage of the warm front. The cold front seems to have passed during the day of the 18th, the wind having changed from southwest to west and the temperature in the same interval having fallen 2°, as compared to the normal rise of 6° from 8 a. m. to 8 p. m. The barograph trace shows a pressure fall from 6 a. m. to 6 p. m. of the 17th, at which time the warm front apparently passed and the pressure ceased to fall. About 10 a. m. of the 18th the pressure again began to fall, continuing until about 4.30 p. m., when the cold front passed and the pressure began to rise.

If thermograph traces are also available they may be used in the analysis of fronts. However, the effect of the daily range of temperature and the variations due to changes in cloudiness disturb greatly the "dynamic" temperature changes, in other words, the changes produced by advection of air masses from warmer or colder regions.

On map 4 (Feb. 17, p. m.) we have placed the eastern part of the warm front W_1 between Jacksonville and Titusville, the reason being that the temperature difference between these stations is 8° while the corresponding difference between Titusville and Miami amounts to only 4° (in spite of the much greater difference in latitude between the two latter). In the same way the temperature difference between Tampa and Apalachicola, which are situated on opposite sides of the front, amounts to 8°. It is seen from the cloud observations at Jacksonville that the warmer air south of the front has begun to slide upward above the P_1 air north of the front. The real verification of this construction comes, however, on the next map (map 5), where the front is displaced northward over eastern Georgia and the Carolina coasts, and a wave accompanied by a rain belt has developed along and to the north of the front. Jacksonville has obviously been passed by the front, for the temperature there has risen 4° during the night against a normal fall of 6° and the wind has changed from west to south. It is interesting to note that Jacksonville which, from the beginning, was north of the front and therefore within the region in which the rain belt developed, has had 0.50 inch of precipitation, while Titusville, which all the while

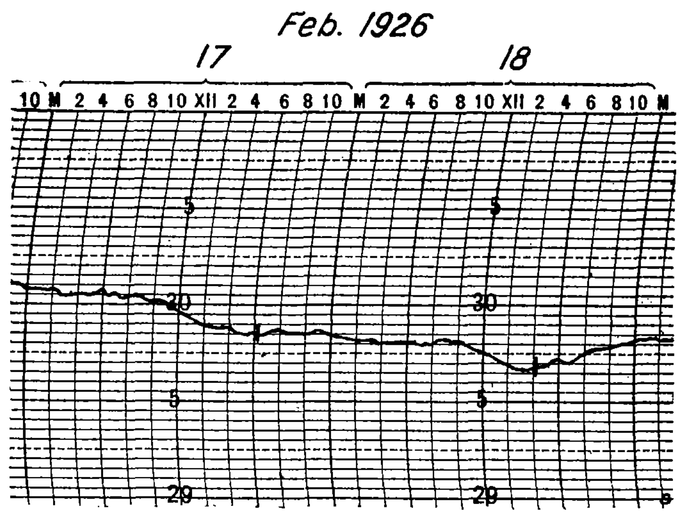


FIG. 3.—Barograph trace at New Orleans, February 17, 18

was in the warm air, got no rain. Also, the temperature at Titusville fell 2° during the night, which is about the amount that usually may be expected, showing that this station remained in the same air mass.

As an example of a cold front let us take the chart 4 of February 17, p. m. The western part of the cold front C_2 was determined in the following manner. Since no definite wind shift line could be found, the temperatures were used. The actual temperatures were compared with the normals for the different stations. It was found that all the stations in the P_2 air north of C_2 had temperatures consistently below the normal. For instance, Santa Fe 28° (normal 36°), Denver 26° (normal 35°), Cheyenne 22° (normal 29°). On the other hand the stations west and south of C_2 show temperatures about normal or a little above; for instance, Lander 28° (normal 27°), Grand Junction 38° (normal 37°), Durango 34° (normal 36°), and Roswell 52° (normal 52°). As seen from the above Durango is a little below normal, but the northwesterly wind, the clear sky, and the nonoccurrence of precipitation indicate that the front C_2 has not yet passed. It is also seen from the map that all the stations east of the front C_2 have cloudy or partly cloudy weather, while Grand Junction and Durango have clear weather. Furthermore, the greatest positive pressure tendencies are located east of the front. Leadville is obviously situated within the warmer P_p air having a northwest wind that agrees with the general drift within the P_p air mass. This may appear inconsistent with the construction, but when it is considered that this station has an elevation of 3,150 meters, which is about 1,500 meters higher than any other station in this immediate region within the cold sector, the inconsistency disappears for the reason that the P_2 current here reaches an elevation between that of Leadville and the surrounding stations.

III. THE AEROLOGICAL DATA

In the discussion of the aerological maps we have excluded the lower levels (below 1,000 m.) in which the observational data are affected by radiation and local conditions. Maps for the 1 km., 1.5 km., 2 km., and 3 km. levels are reproduced in Figures 4–7. For the kite data entered on these maps altitudes are referred to sea level, and for the pilot balloon data to the ground. The discrepancy thus created is insignificant, since the aerological stations, being all in the Middle West and the East, are generally at small elevations; furthermore, where a kite record was available, the wind data also were taken from this record. Thus all the data at the kite stations are referred to the same base. On the maps for the 17th, we have entered the surface observations at Pueblo (1,420 m.) and at Denver (1,613 m.) on the 1,500 m. map, at Durango (1,991 m.) on the 2,000 m. map and at Leadville (3,150 m.) on the 3,000 m. map.

Starting with the maps of February 16th, 8 a. m., we see that at Ellendale, Drexel, and Broken Arrow temperatures at 1,000 m. are about the same, varying between 2.1° C. at Ellendale and 4.0° C. at Drexel, while over the East the temperature at that level is much lower, being −8.9° C. at Washington, D. C.

This contrast extends up to the highest levels reached by kites.

The eastern and southern boundaries of the cold air (P_1) over the Atlantic States are given by the cold front C_1 (see map 1).

The body of the P_1 air, being limited on the east, south, and west, must therefore be dome shaped. The probable configuration of the transition layer between P_1 and the warmer air (M) is indicated by dotted lines for the different levels. The comparatively warm and dry M current will in the subsequent developments serve partly as polar air (in its relations to the warm T_m current from the Gulf appearing on the later maps) and partly as tropical air (relative to the P_2 air mass).

Over the West Gulf States a warmer current (M_1) is penetrating northward in the 1,000 m. level. Since its relative humidity is low as compared with the warm T_m current appearing on the maps of the 17th, it seems justifiable to assume that this M_1 current is of polar origin but during its transport over the Gulf has gradually been heated from below. The probable lateral extension of this M_1 air is given by a dotted line.

On account of lack of aerological data in the West, the distribution of the P_2, P_p and T_p masses can not be determined, but to aid the reader we have transferred to the 1,000 m. map the positions of the fronts at the surface from map 1.

The morning map of February 17th shows a considerable warming at all levels over Washington, 9.6° C. at 1,000 m., 12.1° C. at 2,000 m., and 13.7° C at 3,000 m., indicating that the P_1 air has disappeared, and that Washington is now in the M air. The M_1 air, which on the preceding map was over Groesbeck, has been displaced northeastward and is now moving in the form of a spiral towards the center of the depression over Colorado, as indicated by the warm northeast wind at Drexel. At the 1,500 m. level this station has a temperature considerably above that of the M air at the same level, but it has a rather low relative humidity, 51%, whence we may conclude that it can not be within the T_m current from the Gulf, which is characterized by high humidity (87% at Broken Arrow, 81% at Groesbeck).

Both Broken Arrow and Groesbeck show inversions and changes in wind direction at 1,000 m., indicating that the transition layer between T_m and M, at this level passes through the two stations. With increasing height the wind direction in this region becomes southwesterly, the T_m current gradually giving place to a somewhat cooler T_p current. The transition between these two air masses takes place in the layer between 1.5 km. and 2 km., and is characterized by a comparatively high lapse rate (0.54° C. at Broken Arrow; see Sec. IV).

It is interesting to verify our constructions by comparing the temperatures in the M air for the 17th with the corresponding temperatures for the 16th. At the 1,000 m. level we had on the 16th temperatures averaging 3° C. and on the 17th 2° C.; at the 1,500 m. level the temperatures averaged 1° C. and 0° C., respectively, and finally, at the 2,000 m. level −3° C. and −2° C., respectively.

The P_2 current has on this map reached Ellendale and brought about a marked cooling.

The maps for February 18th show a considerable displacement of the different air masses. The P_2 current has continued to move southward, Drexel as well as Ellendale being now within this air.

The P_p current from the Pacific is moving spirally in towards the center of the LOW, now over eastern Oklahoma. With the arrival of this air the temperatures over Broken Arrow and Groesbeck have fallen. The M_1 and the M air masses have been displaced northeastward, and the T_m current has moved eastward. The boundary between the M and the T_m air is found over Due West at the height of 1,200 m., where there is a well marked inversion with wind shift from ESE. to S.

As a verification of the constructions given on the maps we may again compare the temperatures within the different air masses for the 17th and the 18th within the T_m air. We had at the 1.5 km. level on the 17th temperatures averaging +10° C. and on the 18th +9° C.; similarly at the 2 km. level +8° C. and +6° C., respectively. For the M_1 air the corresponding data at the 1.5 km. level are +4.3° C. and +5.5° C.; at the 2 km. level +1.2° C. and +2.5° C.

The maps for the 19th show a general spreading southward and eastward of the P_2 current, all the kite stations except Due West being now in this current. Due West seems to be within the M_1 air which is best seen if the temperatures there are compared with those at Washington for the preceding day. Thus the temperature in the M air on the 18th at Washington was 8.3° C. at the 1,000 meter level, 5.5° C. at 1,500 m. and 2.5° C. at 3,000 m., while the corresponding temperatures at Due West on the 19th were 8.0° C., 5.0° C., and 3.7° C.

IV. CYCLONIC CONVECTION

A closer study of the warm front rains over the Southern and Central States shows that in one respect they differ widely from the type of warm front rain ordinarily observed in northern and western Europe. In the

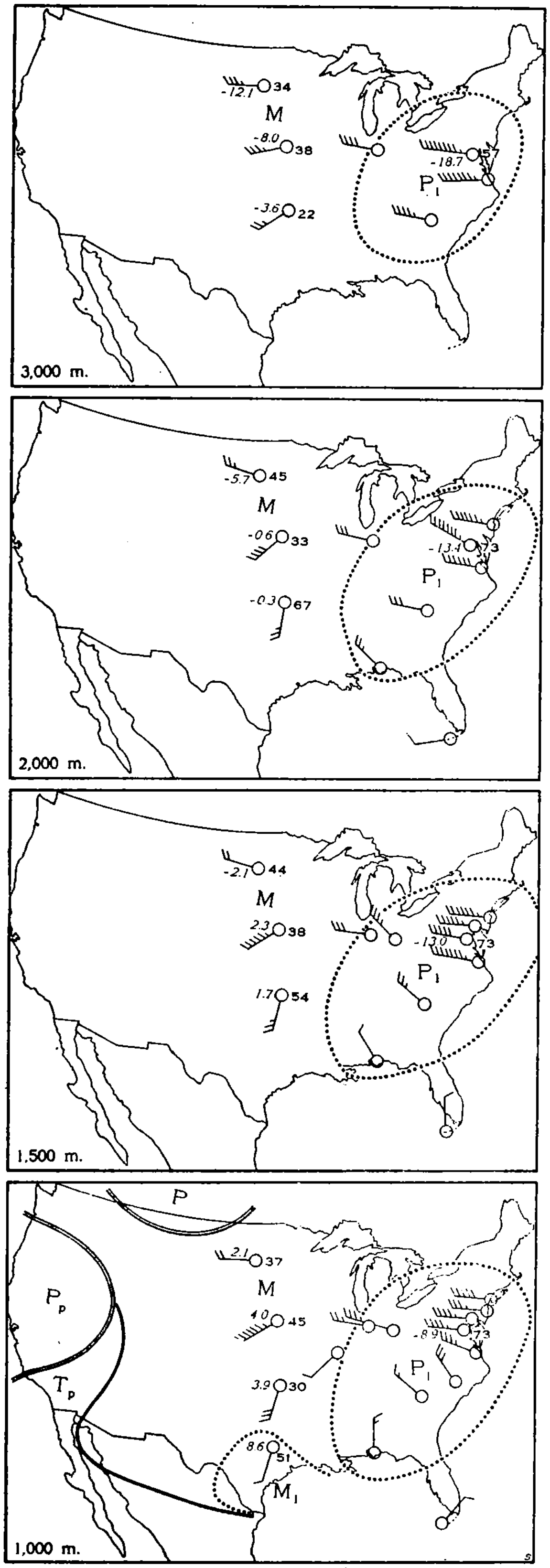


FIG. 4.—Winds, temperatures (degrees centigrade), and humidities in the free air, February 16, 8 a. m. (Fronts in figs. 4-7 as on lithographic charts)

Inversions

Station	Alt. (m.)	Temp. (°C.)	R. H. %	Wind Dir.	Wind Vel.	Alt. (m.)	Temp. (°C.)	R. H. %	Wind Dir.	Wind Vel.
Groesbeck	897	7.6	59	sse.	5.9	997	8.6	51	ssw.	2.9

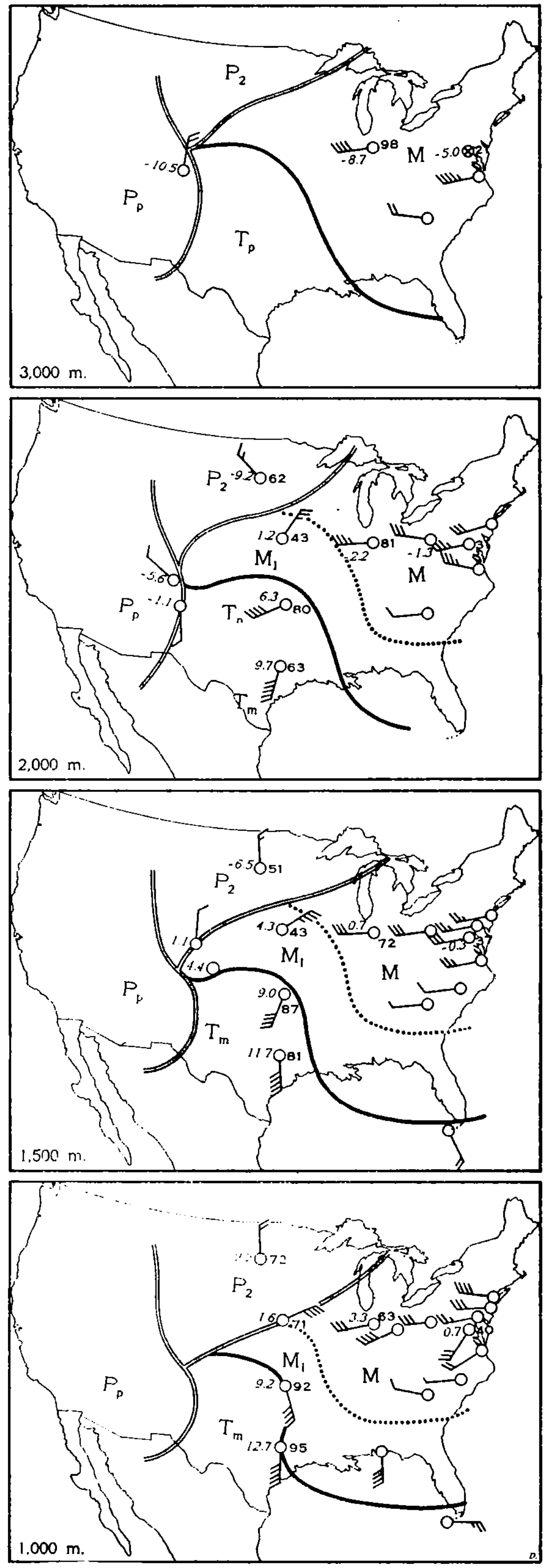


FIG. 5.—Winds, temperatures (degrees centigrade), and humidities in the free air, February 17, 8 a. m.

Inversions

Station	Alt. (m.)	Temp. (°C.)	R. H. %	Wind Dir.	Wind Vel.	Alt. (m.)	Temp. (°C.)	R. H. %	Wind Dir.	Wind Vel.
Drexel	1,040	1.5	71	ene.	15.7	1,357	5.2	43	ene.	14.3
Broken Arrow	894	8.4	92	sse.	16.7	1,197	10.6	91	s.	15.8
Groesbeck	631	12.2	100	sse.	17.7	1,180	12.9	92	s.	21.8
Royal Center	3,100	−9.4	100	w.	15.9	3,173	−8.8	77	w.	19.3

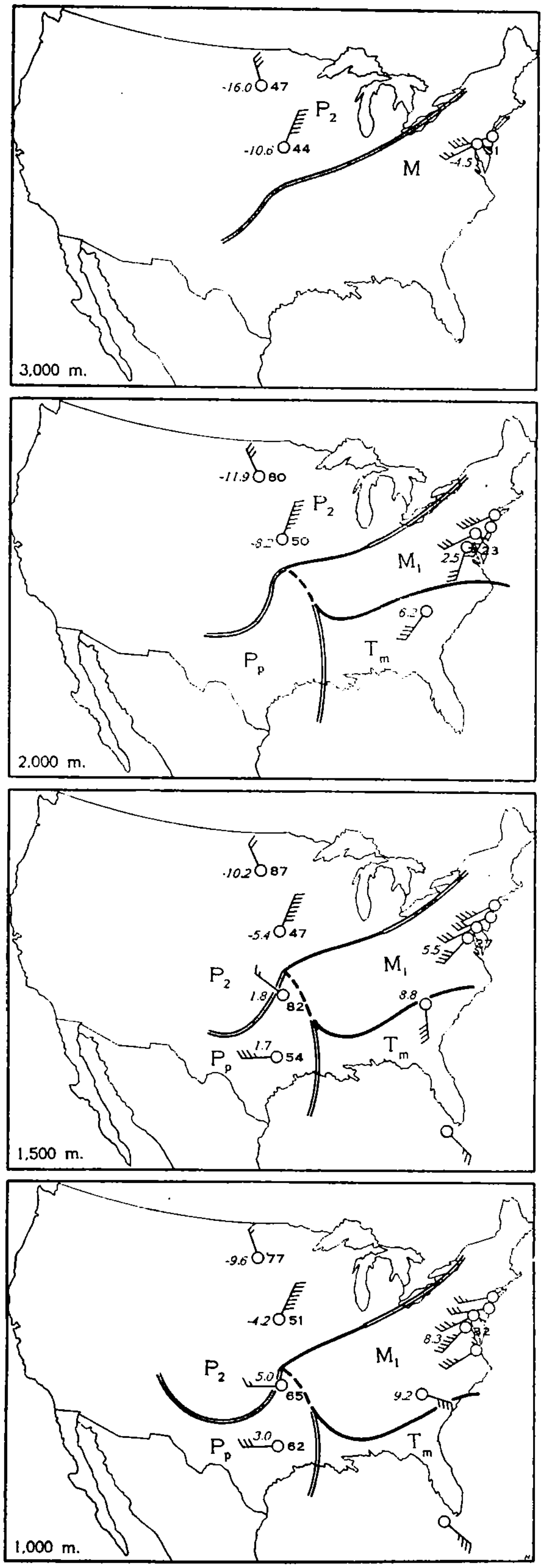


FIG. 6.—Winds, temperatures (degrees centigrade), and humidities in the free air, February 18, 8 a. m.

Inversions

Station	Alt. (m.)	Temp. (°C.)	R. H. %	Wind Dir.	Wind Vel.	Alt. (m.)	Temp. (°C.)	R. H. %	Wind Dir.	Wind Vel.
Groesbeck	1, 337	0. 6	70	w.	11. 7	1, 563	2. 1	48	w.	15. 6
Washington	4, 126	−14. 0	51			4, 360	−12. 8	65		
Due West	1, 149	8. 7		ese.	17. 8	1, 248	11. 1		s.	15. 1

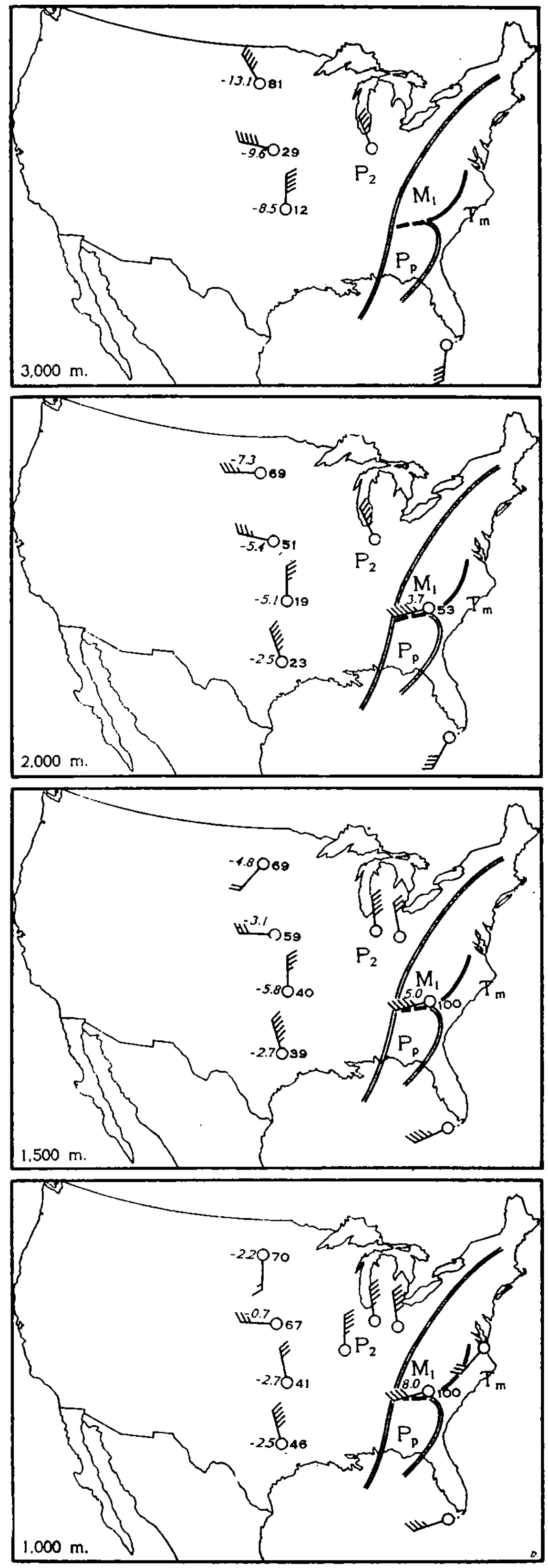


FIG. 7.—Winds, temperatures (degrees centigrade), and humidities in the free air, February 19, 8 a. m.

Inversions

Station	Alt. (m.)	Temp. (°C.)	R. H. %	Wind Dir.	Wind Vel.	Alt. (m.)	Temp. (°C)	R. H %	Wind Dir.	Wind Vel.
Broken Arrow	1, 558	−6. 2	40	n.	13. 5	1, 701	−4. 2	22	n.	13. 2
Groesbeck	1, 252	−3. 2	45	nnw.	20. 8	1, 792	−2. 2	31	nnw.	21. 7
Due West	2, 018	3. 7	50	wsw.	18. 9	2, 186	5. 2	32	wsw.	24. 8

latter, the precipitation is evenly distributed over a large area. Beginning as light rain, starting at high levels, it gradually increases in intensity as the rain belt advances. Seldom, if ever, is it associated with convection phenomena. If we now turn to the warm front rain along W_1 (Map 4 *et seq.*) we find it accompanied by squalls and heavy thunderstorms. These thunderstorms can not have their origin in surface convection. Fort Smith and Vicksburg, which both reported thunderstorms on the evening of the 17th, were within the rain belt on the morning of the same day and remained there during the day. Thus, on account of the thick cloud layer, the effect of direct solar radiation in producing heat convection from the ground was eliminated. This becomes still more evident if the kite ascents at Broken Arrow and Groesbeck are taken into consideration. They show southerly winds within the lowest 1,500 meters with lapse rates less than 0.4° C. per 100 m., indicating a stable stratification. Thus we are forced to localize the thunderstorm-producing convection in the free atmosphere above 2,000 m., to which height the kites rose during the 17th.

In order to explain thunderstorms of this type we may assume that, through suitable advection at different levels, relatively warm air masses have been brought in under a colder current in such a way that at a certain height the stratification has become unstable. Thus, in the case under discussion, as the center D_1 approached the Mississippi Valley, the moist and warm air over the Gulf was accelerated northward and brought in below an upper, somewhat colder southwesterly current.

This assumption is supported by the aerological maps for this period. On the morning of the 17th (fig. 5) we have over the West Gulf States a warm moist T_m current from the south extending up to about 1,500 m. At this level the wind slowly changes to southwest and west-southwest, the T_m current gradually giving place to a somewhat colder T_p current. At the same time the vertical temperature fall becomes steeper. Between 500 m. and 1,000 m. the lapse rate is only 0.18° C. per 100 m. and between 1,000 m. and 1,500 m. 0.04° C. but higher up, between 1,500 m. and 2,000 m. it increases to 0.54° C., which is just about equal to the adiabatic lapse rate for saturated air of this pressure and temperature. Since the relative humidity at these levels ranges from 80% to 87%, it is clear that only a small upgrade movement is needed to start condensation. Once condensation has begun, the air will continue to rise with increasing velocity as long as there is any water vapor left.

There is nothing to produce such an upgrade movement within the warm sector of the cyclone, but along the warm front where the T_m air is forced to ascend above the surface layer of colder P_1 (or M_1) air, the vertical components are sufficiently great to start condensation. Thus we will have a more or less thin, warm, moist T_m current sliding up over the warm front, between the P_1 air below and the T_p air above as through a funnel. Along the warm front surface we have a smooth cloud layer, due to the slow upgrade movement of the T_m air and corresponding to the warm front cloud layer as described by Bjerknes and Solberg. Above this cloud layer, where the lapse rate is unstable, violent convection sets in, giving rise to huge Cu. Nb. clouds attended by squalls and sometimes thunderstorms. The reason why this convection does not spread downward is that the boundary between the P_1 and T_m currents is characterized by a temperature inversion, impenetrable by eddies.

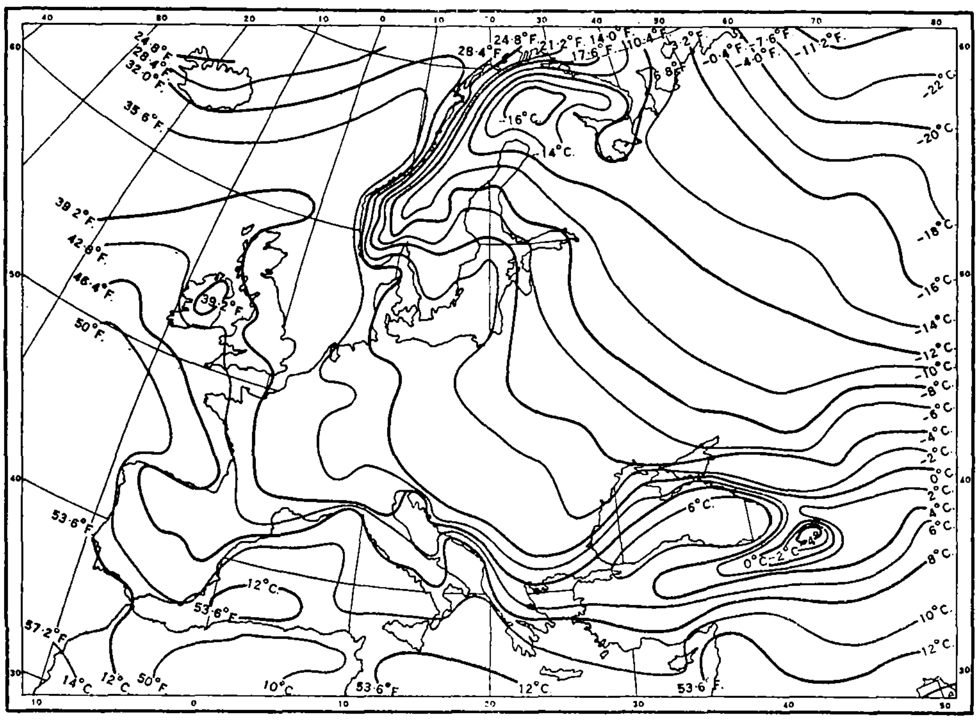


FIG. 8.—January isotherms over Europe

Why do not the causes which produce the above described kind of cyclonic convection give the same results in northern and western Europe? The answer is to be found in the different distribution of land and water surfaces. In Europe there is a large land area in the south with a comparatively warm ocean to the north and west, while in the Gulf region the distribution is just the opposite. In winter, the European continent is generally covered by a layer of cold, polar air. The cyclones, which move northeastward along the coast, generally have the form of long narrow tongues of warm air pointing northeastward. On account of this form they generally occlude very rapidly. Even if within the warm sector of a cyclone the lowest layers are moving

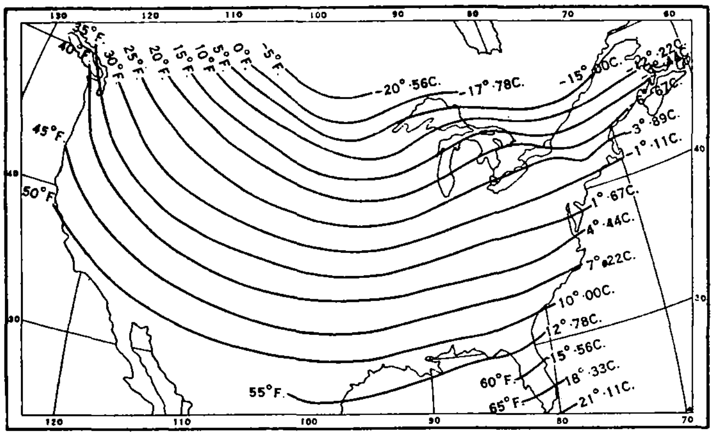


FIG. 9.—January isotherms over the United States

northward relative to the upper current, this does not necessarily mean any tendency to the creation of supera-

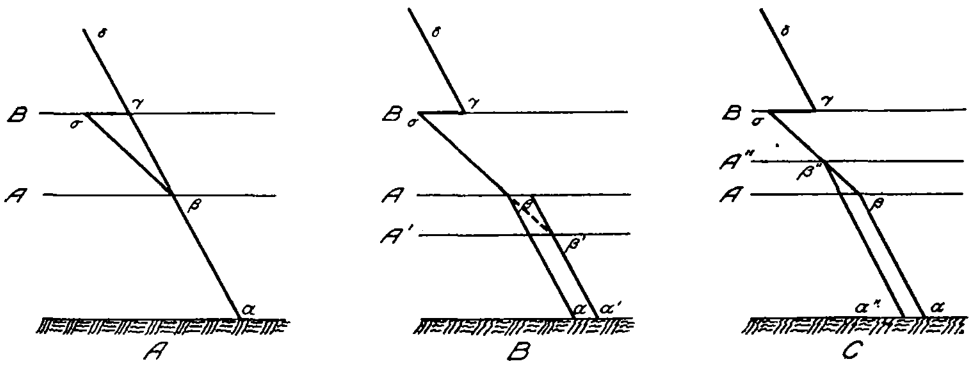


FIG. 10.—Ideal vertical distribution in overrunning cold front

diabatic lapse rates in higher levels. The reason for this is that normally, at least at the surface, there is hardly any latitudinal temperature gradient over northwestern Europe (fig. 8). In certain parts of this region the peculiar distribution of land and water has even produced a reversed temperature gradient.

In summer, conditions in northern Europe are more favorable for the development of cyclonic convection, since the continent has become heated to a temperature considerably above that of the Atlantic. However, the warm continental air does not carry enough moisture to produce any considerable instability and convection.

If we now observe the January isotherms for the Gulf States (see fig. 9), we see, that at New Orleans the latitudinal temperature gradient at the surface amounts to about 2.6° C. per 100 km. If within the lowest 2 km. the average vertical temperature lapse rate is 0.4° C. per 100 m. and the air is given such a movement northward that the total displacement at the surface is equal to 200 km. and at the 2 km. level is equal to zero, then through this displacement the average vertical lapse rate will increase to 0.66° C. per 100 m., which is considerably above the adiabatic lapse rate for saturated air. It is obvious then that almost any slight, occluded disturbance which approaches the Mississippi Valley from the northwest will accelerate the air over the Gulf enough to produce potential instability.

There is another kind of upper air convection which plays an equally or even more important rôle in the United States, namely, that caused by the passage in higher levels of a cold front over a warmer surface current. This type of convection, the importance of which has often been emphasized (though not in print) by Mr. Choate of the United States Weather Bureau,[3] is so significant for American weather that treatment of it here, in connection with the more general question of cyclonic convection, seems desirable, even though the map series under discussion offers no very striking example of this phenomenon.

If two currents of very different density, the one of polar and the other of tropical origin, are kept in balance side by side through suitable relative movements and then, for some reason, this motion stops, the heavier mass will have a tendency to sink to the ground and to spread under the warmer and moister air as a thin, cold layer. If, however, the difference in density (temperature) is very slight, the colder air may spread out in an intermediate level and thus float on the top of a warm current.

If the original vertical temperature distribution within the warm air is given by the line $\alpha\beta\gamma\delta$ in Figure 10A and the overrunning takes place between the two levels A and B, the resulting temperature distribution will be $\alpha\beta\sigma\gamma\delta$. From this graph we see that the upper

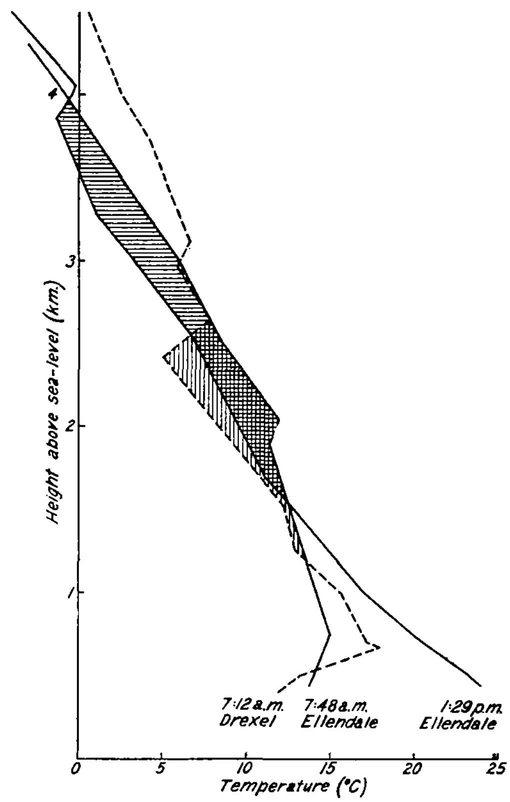


FIG. 11.—Vertical temperature distribution at Ellendale and Drexel, October 10, 1923

[3] See page 495. An unpublished manuscript embodying Mr. Choate's views on this subject is on file in the Weather Bureau at Washington.

boundary of the cold current is now characterized by an inversion and increased stability. In the lower levels, where the polar current is in contact with the underlying moist air, the stability has decreased or even changed into instability; as a consequence, convection is likely to occur.

A good example of this overrunning is found in the kite ascents at Drexel and Ellendale for October 10, 1923, Figure 11.[4] On the morning of this day both stations, which are situated on the eastern side of a trough, have surface winds from SSE. At Ellendale, the wind between 1,250 m. and 1,500 m. turns to south and remains south up to the top of the flight, 4,300 m. The relative humidity decreases gradually to 27% from the surface up to 3,200 m. and then slowly rises to 73% at 4,300 m. There is a surface inversion and a weak inversion at the 2,000 m. level, the lapse rate being small at all heights. At Drexel, the wind between 1,250 m. and 1,500 m. turns from S. to SSW., while the temperature lapse rate increases. Between 1,564 m. and 2,000 m. the wind again backs to S. In this layer the lapse rate reaches its maximum value, 0.8° C. per 100 m. From 2,420 m. up to 2,644 m. there is a well developed inversion with a rapid decrease in relative humidity.

Comparing the two stations we find that, except in the radiation cooled surface layers, the temperatures at Drexel up to a height of 1,250 m. are higher than the corresponding temperatures at Ellendale, as one would naturally expect on account of the difference in latitude. At 1,250 m. Drexel is only 0.5° C. warmer than Ellendale. At the 1,500 m. level Drexel becomes colder than Ellendale and at 2,000 m. the difference amounts to 3.5° C. At 3,000 m. Drexel is again warmer than Ellendale. Thus it looks as if a colder current with a slight westerly component is coming in over Drexel between 1,500 m. and 2,420 m.

If this supposition is correct, we may expect to find this same current better developed in the afternoon flight at Ellendale. This is found to be actually the case. The flight shows southerly winds up to 1,250 m. At 1,500 m. the wind changes to SSW. and so remains up to 3,855 m., where it again changes to S. It is interesting to note that, while in the lower levels the temperature during the day has risen, and at 1,500 m. remained constant, higher up with the change in wind direction to SSW., it has fallen considerably, for instance 2.3° C. at 2,000 m., 2.7° at 3,000 m., and 2.3° at 3,500 m. In the highest layer, where the wind has remained unaltered, the change is very small, e. g., −0.3° C. at 4,000 m. Thus we may conclude that the cold current has now reached Ellendale and is spreading out in a layer between 1,500 m. and 4,000 m. As we should expect, we find an inversion at the upper boundary of the cold current, where the temperature rises from −1.3° at 3,855 m. to 0.2° C. at 4,059 m.

In general, the overrunning cold front will not deviate materially in wind direction from the surface current, on account of the turbulence and strong convection at its lower boundary.

Suppose that the cold front, as it advances, overruns air of gradually increasing temperature. This can be represented in the temperature diagram (fig. 10 B) by a displacement to the right of the curve $\alpha\beta$ to the new position $\alpha'\beta'$. Thus the plane A would be characterized by a sudden drop in temperature. The resulting temperature distribution, being strongly unstable, will immediately give rise to turbulence and overturning. As a consequence, the two air masses will mix to some extent but the main result will be a sinking of the polar current down to the level A′, where the prolongation of $\sigma\beta$ intersects the temperature curve $\alpha'\beta'$.

On the other hand, if the polar current overruns air of gradually decreasing temperature, it will be lifted to a point where $\sigma\beta$ and the new temperature curve $\alpha''\beta''$ intersect (fig. 10 C).

We have now seen how it is possible for the cold air to float on top of a warm current. We must, however, explain the origin of this stratification. For this purpose, we take the topography of the Western States into consideration. A cold current from the Pacific is not able to pass the Rocky Mountains until so much cold air has accumulated that it reaches the summit of the range. Then the upper layers of this cold Pacific air will gradually begin to flow over the range through the mountain passes and, unless the lapse rate within the air east of the mountains is very high, this Pacific air will not immediately penetrate down to the surface. In spring, when the snow cover on the ground in the Northern Plains States helps to maintain a surface layer of stable, radiation-cooled air, conditions are very favorable for the occurrence of this overrunning. On the contrary, the cold fronts from the north are generally marked by such a decided temperature discontinuity that the cold air immediately sinks to the ground.

As the overrunning cold front advances southeastward it will meet warmer and warmer air. Thus the temperature differences will constantly increase and the free air turbulences will become more and more violent. In a paper printed elsewhere in this REVIEW, Humphreys connects the occurrence of tornadoes with the overrunning of cold fronts and points out that the occurrence of tornadoes is most frequent in spring, when according to the above discussion the conditions for overrunning are most favorable.

It would seem that overrunning should also be possible in northwestern Europe. However, in winter time a mid-air cold front which approaches the European continent from the relatively warm ocean to the northwest, will meet colder and colder air and thus be lifted to higher levels, becoming gradually weaker. In summer time, when the continent is heated, the reverse is true but the continental air is then rather dry, which will counteract the tendency to convection.

Thus we are led back to the question: What is the role of the moisture in the atmosphere and especially, what is the significance of the lapse rate for saturated air? The chief difference between convection in moist air and in dry is this: An atmosphere in which the lapse rate is a little steeper than the moist adiabatic (without reaching the dry adiabatic), and in which the humidity is a little less than 100%, is stable from a purely dynamical point of view. An air particle (fig. 12), which is lifted from its equilibrium position, will expand at first according to the dry adiabatic law, will become colder and heavier than its surroundings and hence will tend to sink to its original position. If the upward displacement is great enough, the water vapor will condense and the temperature change will now follow a psuedo-adiabatic curve. Only, when the forced displacement of the particle is so great that the particle, moving along this pseudo-adiabatic curve, again meets the curve for the actual temperature distribution, will instability result. Thus we see that in an atmosphere where the lapse rate is intermediate between the moist adiabatic and the dry adiabatic and where the humidity is less than 100%, a

[4] This example has been discussed by Mr. Choate.

finite displacement is necessary in order to start convection and the less the humidity the greater the displacement required. Thus we may, through suitable advection, increase the lapse rate to almost the dry adiabatic and in this way store up a considerable amount of energy which, once convection has started, may suddenly be made available for the production of turbulent energy. We may say that an atmosphere with the above-described stratification is dynamically stable but thermodynamically unstable.

On the other hand, within a dry atmosphere with superadiabatic lapse rate, any displacement of a particle will immediately start convection and prevent the development of highly superadiabatic lapse rates. Great amounts of potential energy in this case can never be stored up and violent turbulence is, therefore, not very likely to occur.

The conception of cyclonic convection is not new in American meteorology but can be traced as far back as

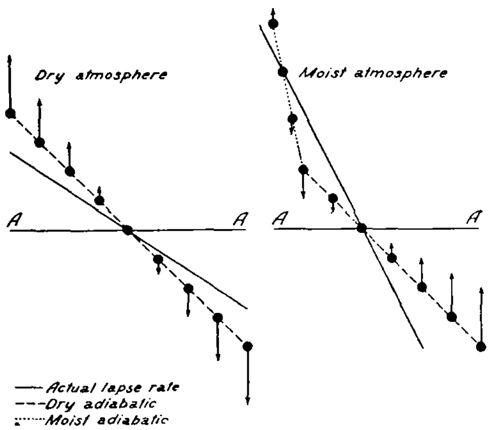


FIG. 12.—Instability in a dry and in a moist atmosphere. Length of arrows is proportional to the force acting on a particle which has been displaced from its equilibrium position in the plane AA

Ferrel's condensation theory. In later years the idea of convection arising from instability produced by suitable relative movements of superposed air layers was used by Humphreys,[5] to explain the thunderstorms that frequently occur in the southern quadrants of a LOW. Here, according to Humphreys the upper winds are westerly while in the surface layers, on account of friction with the ground, the wind has a southerly component. As a consequence of this wind distribution warmer and warmer air is brought in below, instablilty results and convection starts. Mr. Choate, through his studies of kite records at Drexel and other stations, has been led to the conclusion that a large percentage of the cyclonic rainfall must be attributed to convection which begins at some distance above the ground, due to relative movements of superposed air layers. As pointed out above he has specially emphasized the frequent occurrence of overrunning cold fronts.

V. CONCLUSION

The present distribution of meteorological stations in the United States has been brought about as a very gradual development by the addition of a few stations at a time. The weather map of January 1, 1871, shows that of the 29 stations reporting by telegraph, 11 were along the Gulf and Atlantic coast, 8 along the Lakes and 10 in the interior. Of the latter 10, only 2 were west of the Mississippi River. During the next 10 years the number had increased to 91 and in the following decade to 128. By 1900 there were 139, by 1910, 168 and at present between 180 and 190. At first the determining factor in the establishment of stations was the location of the Signal Corps stations, where telegraph facilities and observers were available and the further fact that the service was inaugurated to protect shipping primarily. Later, when telegraph lines tapped almost every region, the need of serving important industrial and agricultural communities provided the moving reason. Naturally the eastern half of the country had more stations than the West.

The data telegraphed depended first on the needs of the forecasters, supplemented later by demands for publication in the press and on the weather maps and bulletins of certain of the data, limited continually by need for economy in telegraphing.

The groundwork of reports was organized at a time when little was known of forecasting, and the system of reports was later expanded during a period when forecasting was based on the experience accumulated by forecasters in their study of the weather maps, rather than on an understanding of the dynamics of cyclones and anticyclones. Under these conditions meteorological data in considerable detail were not needed. However, as the physical processes became better understood, additions were made in the cloud observations, certain modifications were made in the telegraphing of pressure changes, and last but most important, reports of wind direction and velocity in the free air were added from pilot balloon and kite stations.

In Europe, where the doctrine of "fronts" has received most attention and support, and has reached its greatest development, the several countries have since the war augmented considerably the amount of data telegraphed in the matter of "present weather" and "past weather." If we in the United States are to profit most fully from our increased knowledge of the dynamics of the atmosphere, fuller information than is now available must be secured.

As regards the distribution of stations, it is obvious that over the West they are entirely too scattered to make possible a reliable analysis of the fronts. The topography, which is extremely irregular, not only affects but in many cases actually determines the movements of the fronts, and a network of stations at least as dense as that over the East is necessary for even a rather crude analysis. The constructions given on our maps must therefore be regarded not as final solutions but merely as indications of the most probable positions of the fronts.

In carrying out this study, the kite data have proved extremely valuable for the determination of the extent and the actual properties of the different air masses. It seems highly advisable, therefore, that they be made available regularly for forecast work. For that purpose they ought to be telegraphed daily, if possible twice daily, to the different forecast centers. The morning kite flight can not be made available to the forecaster in time for his morning forecast work, but would prove extremely helpful in issuing cold wave or storm warnings in the afternoon, and also for the regular evening forecasts.

The beginner especially is very apt to discuss the fronts in a schematic way, neglecting to consider the relative strength of the fronts, in other words, the potential energy available for transformation into kinetic energy. A proper estimate of this is only possible if upper air temperatures are taken into account.

[5] Physics of the Air, Philadelphia, 1920, p. 347.

Furthermore, in the forecasting of cyclonic convection of the kind described in Section IV, the use of kite data is almost indispensable. A kite flight from Groesbeck or Broken Arrow, combined with a few pilot balloon runs and surface data from the Gulf region, can tell how much of a relative displacement of the different air layers is necessary to produce instability and free air convection.

The surface observations in the United States are not so detailed as in Europe where, since the war, forecasting methods in practically all countries demand very specific and detailed information. In the United States the time interval between consecutive maps is 12 hours, which is too long, especially in the case of rapid developments and rapid movements. An intermediate pressure map, say at 2 p. m., would be of much assistance.

The element which has perhaps proved most valuable in tracing the fronts is the barometric tendency or the pressure change in the 2 (in Europe 3) hours preceding the observation. According to the new international code now used in Europe this element is given by two figures, the first (the characteristic) giving a description of the general form of the pressure curve (for instance, first falling, then stationary), while the second gives the total amount of the pressure change. The "characteristic" has proved of great value for the determination of the exact positions of the fronts since, as pointed out in Section II, the warm and cold fronts generally are associated with typical forms of pressure curves (cold front: first falling or stationary, then rising; and warm front: first falling, then stationary). The necessity of introducing the characteristic on the American weather maps as one of the principal elements can therefore not be too strongly emphasized. According to the system now in use in the United States, pressure changes smaller than 0.04 inch are not telegraphed. It is suggested that this limit be lowered to 0.02 inch since the characteristic tendencies accompanying weak or occluded fronts are generally very small.

The weather at the time of observation is according to the new international code given by two numbers, making it possible to distinguish between 100 different types of weather. A closer study of synoptic maps soon shows that the different fronts and sections of the cyclones are characterized by very well-defined weather types as a rule. This elaborate scale has therefore become a very important instrument in the analysis. Doubtless the five classifications now in use in the United States are entirely too few to meet the demands of the situation, although we should not necessarily suggest an increase to 100. Also some information concerning the weather between the observations would be of very great value.

It is believed that the above study has furnished conclusive evidence that the polar front theory can be applied with great advantage to even rather complicated weather maps in the United States and that it enables us to explain phenomena which without a knowledge of the dynamics of the situation would hardly be understood. For instance, the rapid dissolution of the rain belt over southern Washington and northwestern Idaho on Map 1 as well as the corresponding disappearance of the rain belt on Map 4 over Oklahoma, Arkansas, and Mississippi can only be explained as the effects of occlusion, a conception which in itself is a product of the polar front theory.

It is not to be expected that a detailed analysis could be made of every map in the actual forecast work. However, a discriminating study of a number of typical weather situations, distinguishing the significant features of these types from the incidental, would probably enable the meteorologist to recognize these types after a brief survey of any map. For that purpose the improvements in observational data pointed out above seem to be necessary.

ACKNOWLEDGMENT

It is a pleasure to acknowledge the valuable assistance which H. C. Willett of the Forecast Division has rendered in the preparation of the maps. During the carrying out of this study we have profited by frequent discussions with our colleagues in the Weather Bureau, especially W. P. Day, who has offered valuable suggestions.

LIST OF SOME TREATMENTS OF THE POLAR-FRONT THEORY

A. In "Geofysiske Publikationer," Oslo

Volume I, 2.—J. Bjerknes. On the Structure of Moving Cyclones.

Volume II, 3.—J. Bjerknes and H. Solberg. Meteorological Conditions for the Formation of Rain. Summary in M. W. R., vol. 50, p. 402.

Volume III, 1.—J. Bjerknes and H. Solberg. Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation. Summary in M. W. R., vol. 50, p. 468.

Volume III, 6.—J. Bjerknes. Diagnostic and Prognostic Application of Mountain Observations.

B. In "Quarterly Journal of the Royal Meteorological Society," London

Volume 46.—V. Bjerknes. The Structure of the Atmosphere when Rain is Falling.

C. In the Monthly Weather Review, Washington

Volume 47, No. 2.—V. Bjerknes. Weather Forecasting.
J. Bjerknes. On the Structure of Moving Cyclones.

Volume 49, No. 1.—V. Bjerknes. The Meteorology of the Temperate Zone and the General Atmospheric Circulation.

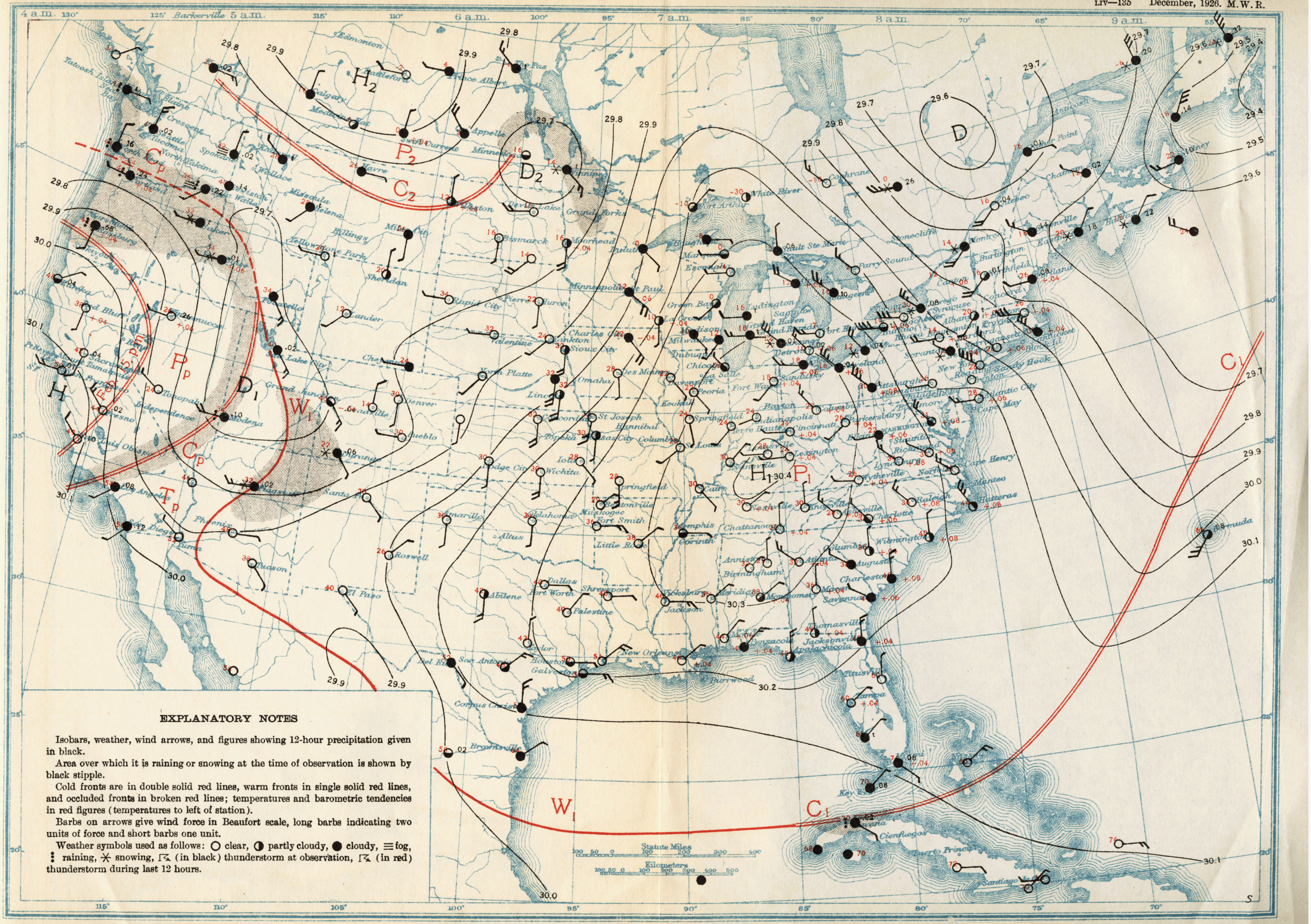
Volume 52, No. 11.—J. Bjerknes and M. A. Giblett. An Analysis of a Retrograde Depression in the Eastern United States of America.

Volume 53, No. 9.—R. H. Weightman. Some Observations on the Cyclonic Precipitation of February 22–23, 1925, in the Central and Eastern United States.

In addition the two following papers in German should also be included in this list. The first gives a summary of the polar front theory and the arguments for and against it, while the second contains an application of the theory to a series of European weather maps.

H. Ficker: Polar-front, Aufbau, Entstehung und Lebensgeschichte der Zyklonen. Met. Zeitschrift, March, 1923.

T. Bergeron and G. Swoboda: Wellen und Wirbel an einer Quasistationären Grenzfläche über Europa, Veröffentlichungen des geophysikalischen Instituts der Universität Leipzig, Bd. III, Heft 2. (See review by H. Willett, Mo. Wea. Rev., Nov., 1926.)



EXPLANATORY NOTES

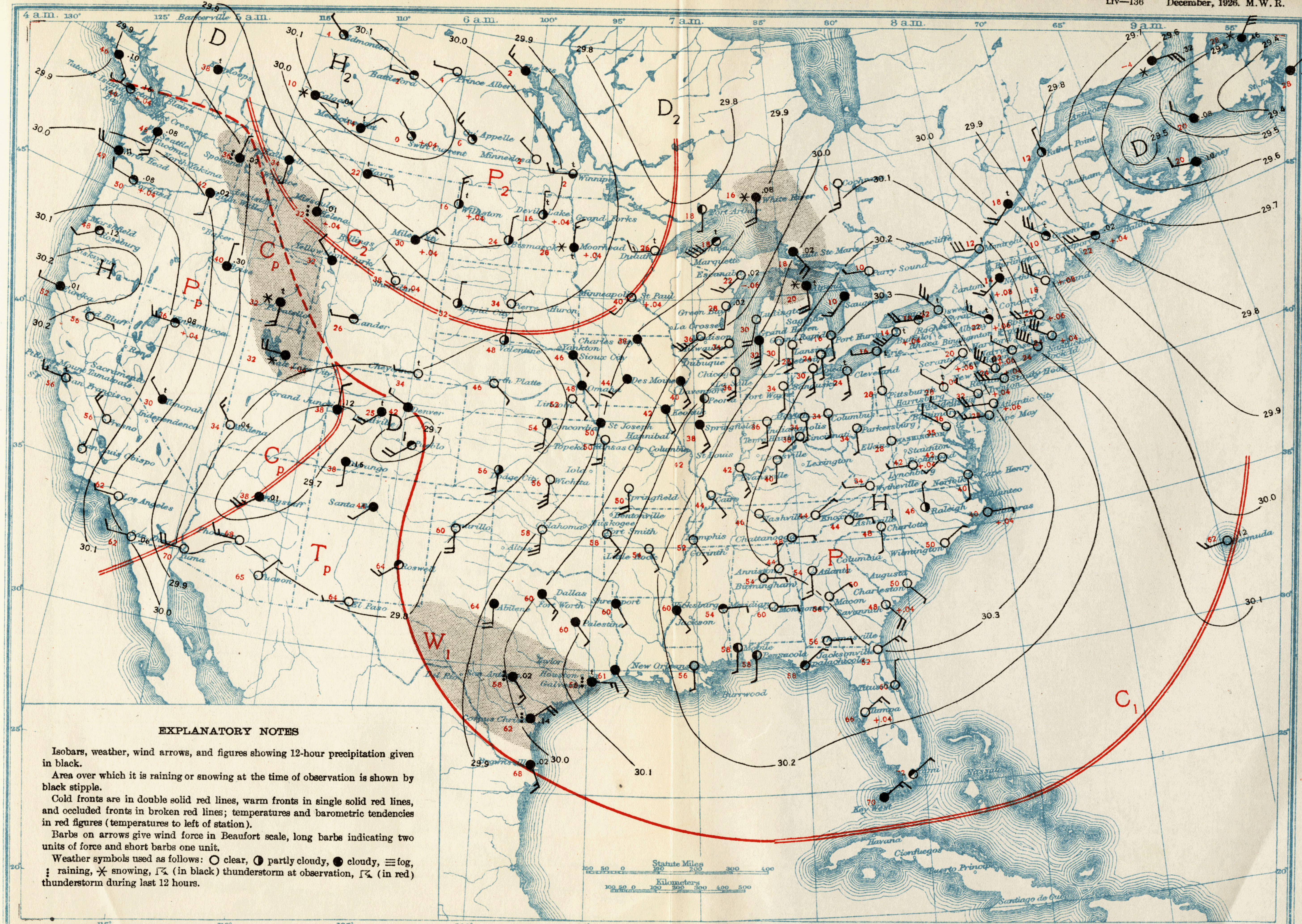
Isobars, weather, wind arrows, and figures showing 12-hour precipitation given in black.

Area over which it is raining or snowing at the time of observation is shown by black stipple.

Cold fronts are in double solid red lines, warm fronts in single solid red lines, and occluded fronts in broken red lines; temperatures and barometric tendencies in red figures (temperatures to left of station).

Barbs on arrows give wind force in Beaufort scale, long barbs indicating two units of force and short barbs one unit.

Weather symbols used as follows: ○ clear, ◑ partly cloudy, ● cloudy, ≡ fog, ⁝ raining, ✳ snowing, ⨽ (in black) thunderstorm at observation, ⨽ (in red) thunderstorm during last 12 hours.



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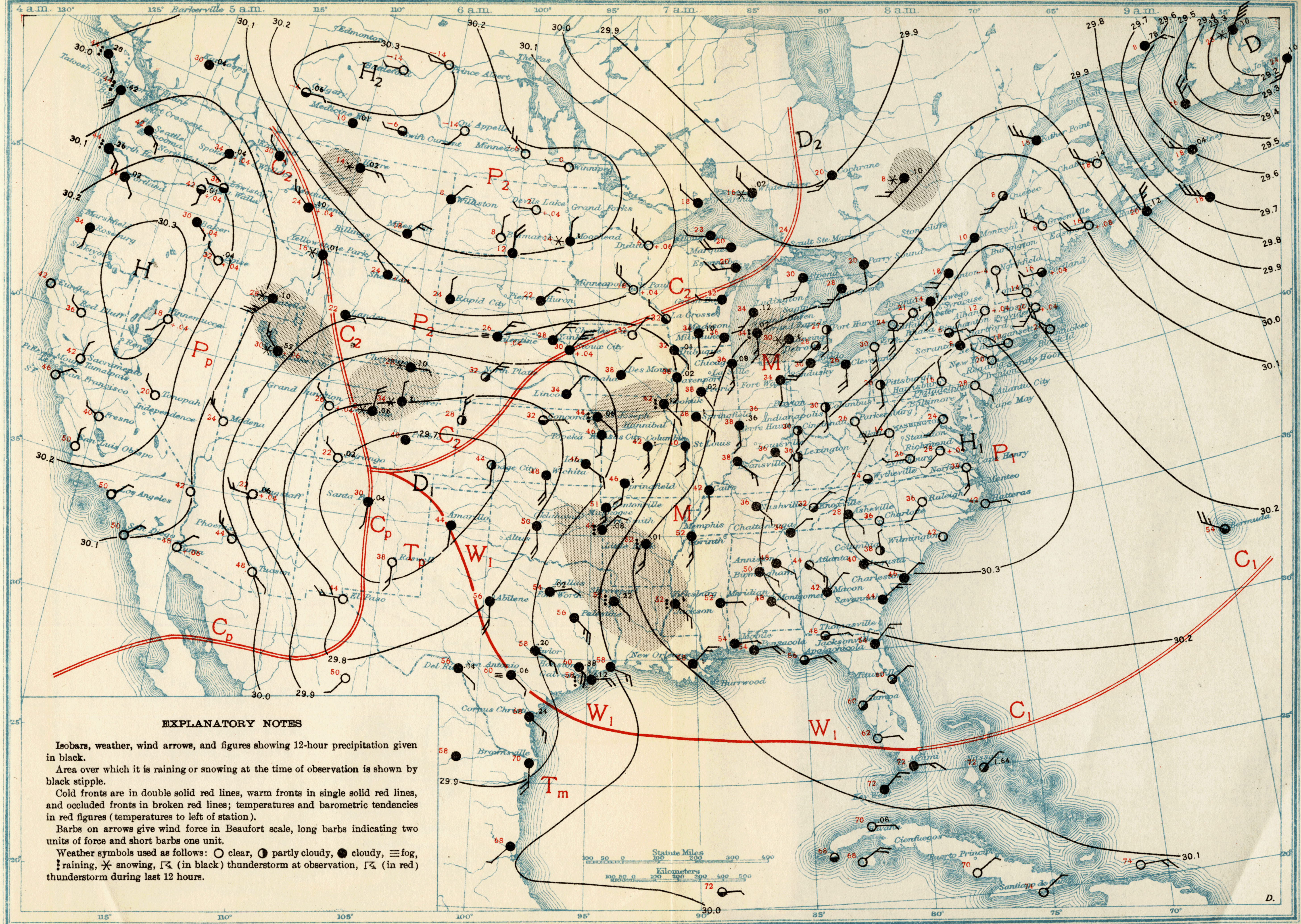

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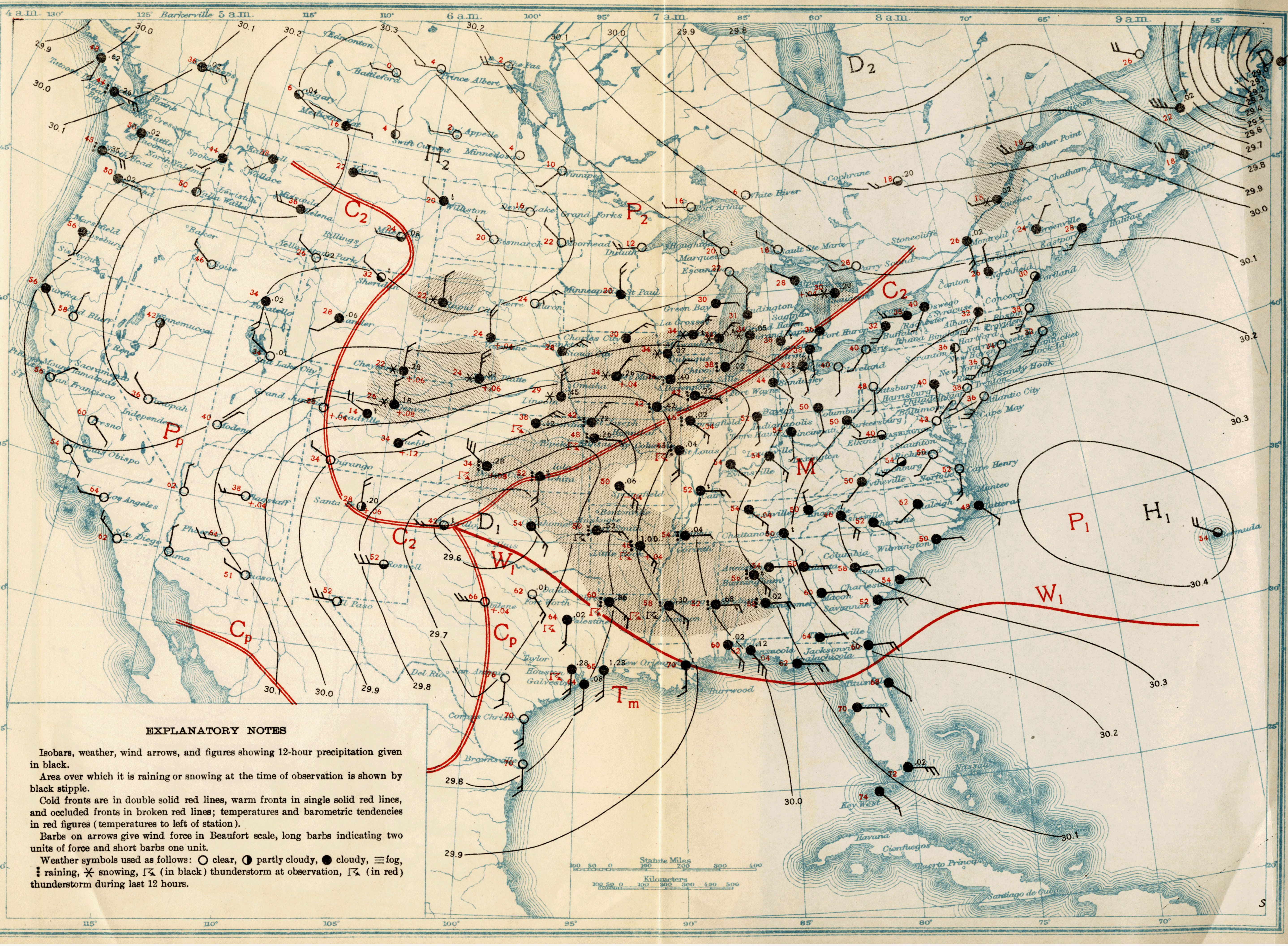

EXPLANATORY NOTES

Isobars, weather, wind arrows, and figures showing 12-hour precipitation given in black.

Area over which it is raining or snowing at the time of observation is shown by black stipple.

Cold fronts are in double solid red lines, warm fronts in single solid red lines, and occluded fronts in broken red lines; temperatures and barometric tendencies in red figures (temperatures to left of station).

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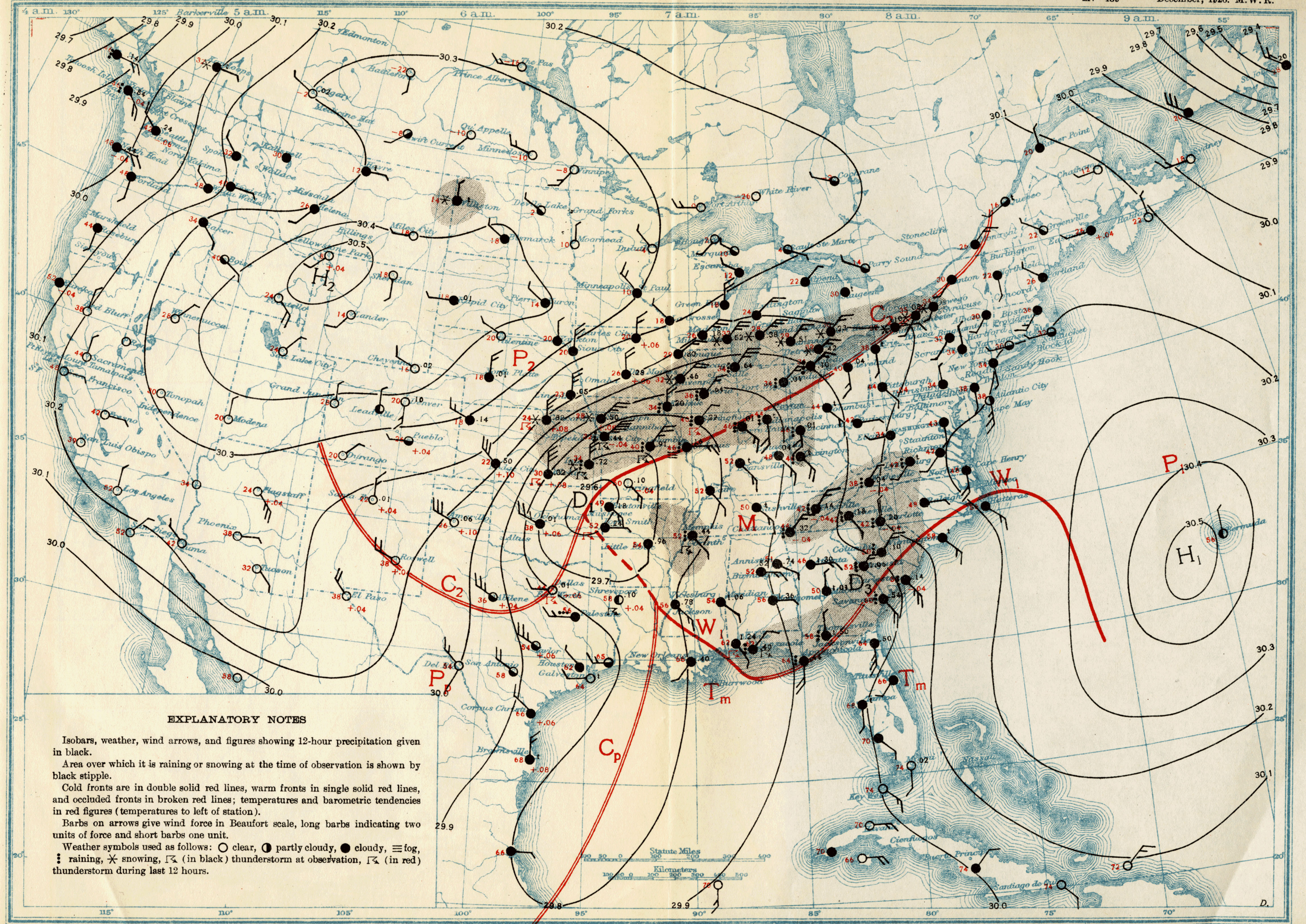

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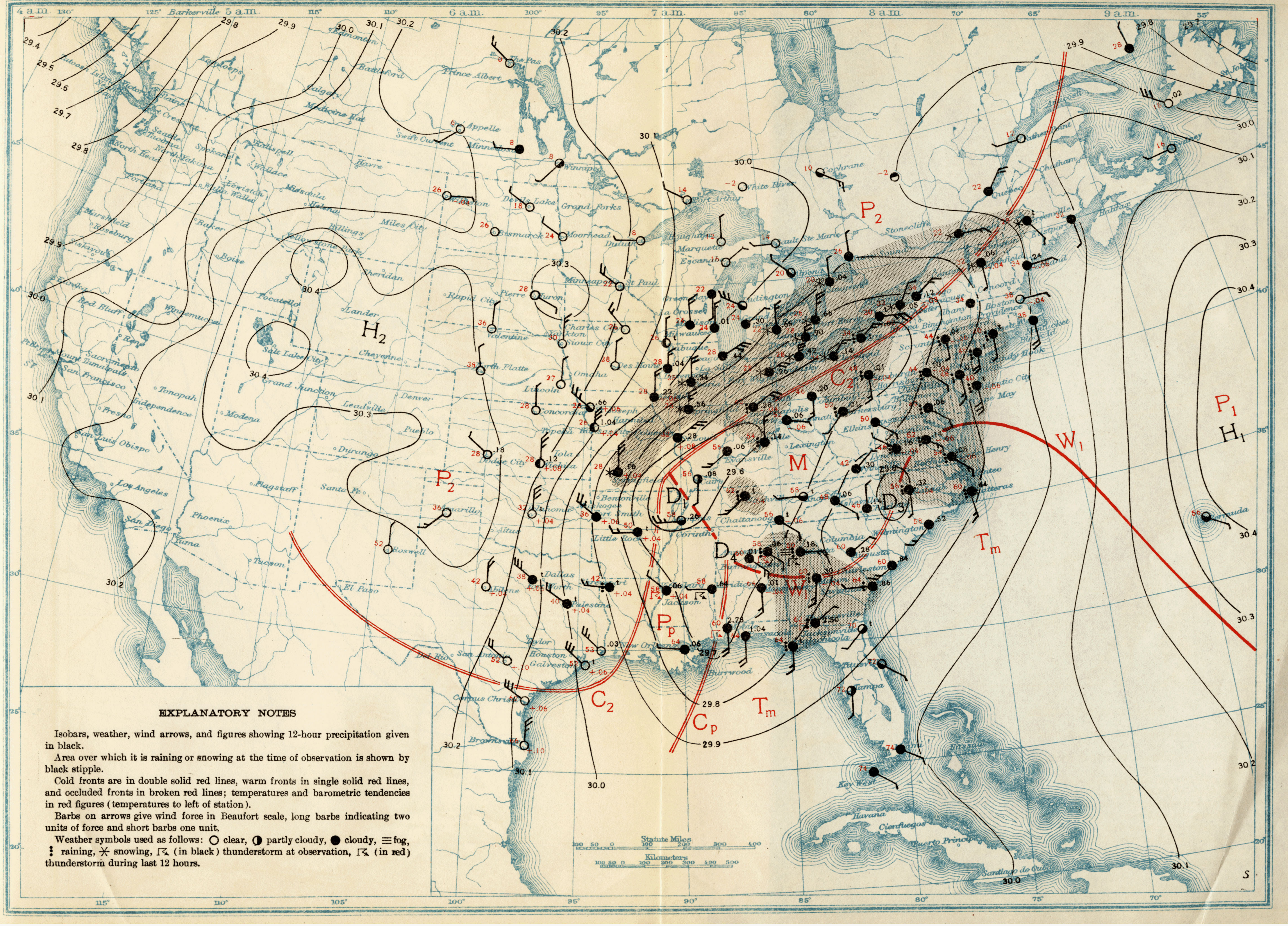

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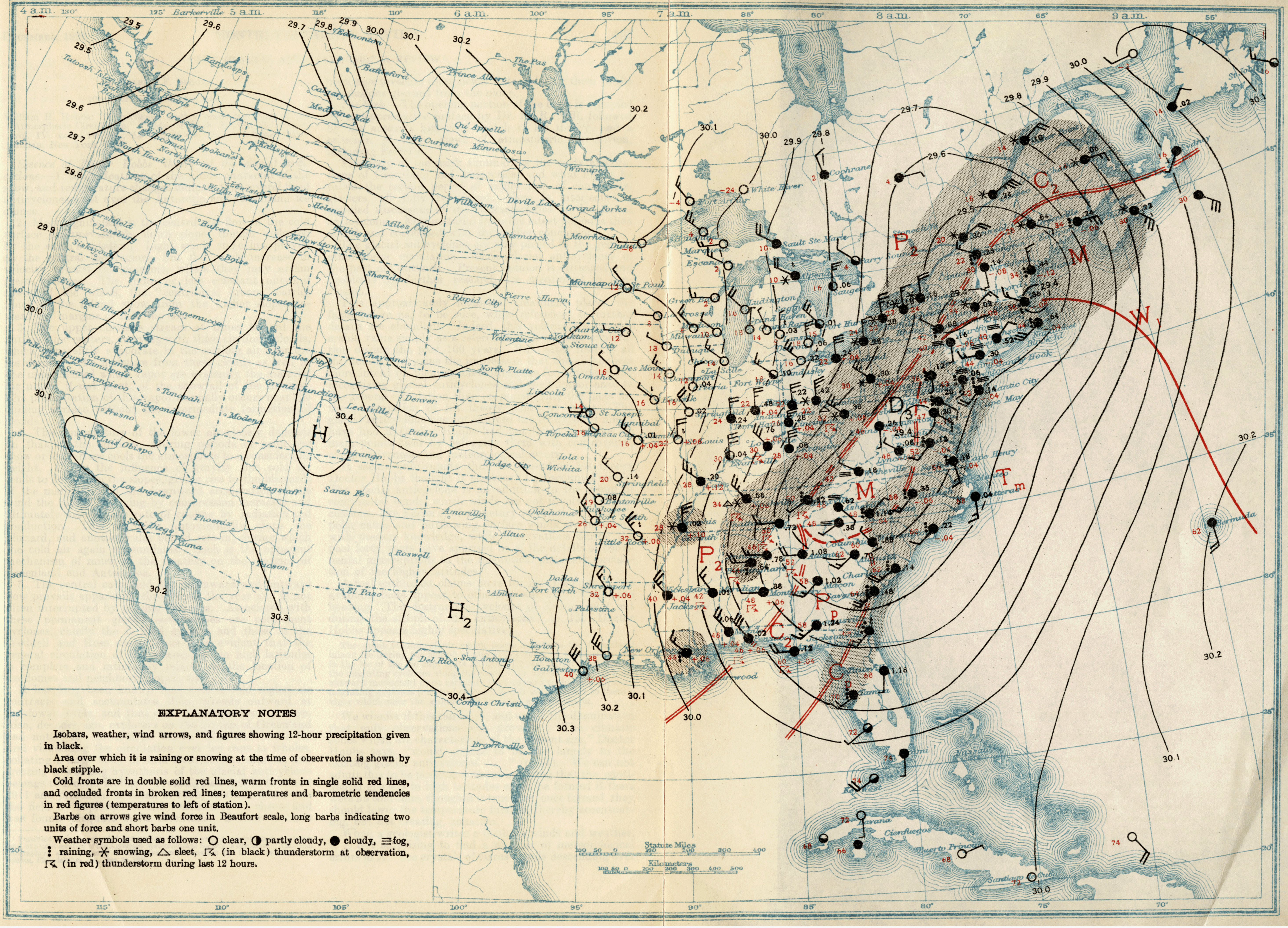

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